Charging for Network Security Based on Long-Run Incremental Cost Pricing

Hui Yi Heng, *Student Member, IEEE*, Furong Li, *Senior Member, IEEE*, and Xifan Wang, *Fellow, IEEE*

***Abstract*—Pricing for the use of the networks is essential in the way that it should be able to reflect the costs/benefits imposed on a network when connecting a new generator or demand and to provide forward-looking message to influence the site and size of future network customers. Studies have been extensively carried out over the years to achieve this pricing goal. Few methodologies can directly link nodal generation/demand increment to network long-run marginal/incremental costs. Even fewer consider network security in their pricing methodologies, considering it is one of the most important cost drivers. All networks are designed to be able to withstand credible contingencies, but this comes at a significant cost to network development. This paper proposes a new approach that can establish the direct link between nodal generation/demand increment and changes in investment cost while ensuring network security. The investment cost is reflected by the change in the spare capacity of a network asset from a nodal injection, which is in turn translated into an investment horizon, leading to the change in the present value of a future investment cost. The security is reflected in the pricing through a full $\mathrm{N}-1$ contingency analysis to define the maximum allowed power flow along each circuit, from which the time horizon of future investment is determined. This paper illustrates the implementation of the proposed pricing model for a system whose demand grows either at a uniform rate or at variable growth rates. The benefits of introducing security into the long-run pricing model are demonstrated on the IEEE 14-busbar system and a practical 87-busbar distribution network.**

***Index Terms*—Long-run incremental cost pricing, maximum loadability, power system economics, power system security.**

I. Introduction

In the U.K., privatization of the electricity supply industry was introduced in 1990, where the underlying concepts were to introduce competition (where competition was deemed possible) and regulation (where competition was not considered practicable, that is, in the natural monopoly functions of transmission and distribution). Since then, market forces are increasingly playing an important role in the development and operation of the electricity supply industry. The main purposes of privatization were to promote competition (improving efficiency, thus reducing prices) and to improve the economic performance of the electricity supply infrastructure while maintaining the security and the quality of supply.

Manuscript received June 18, 2008; revised March 06, 2009. Current version published October 21, 2009. Paper no. TPWRS-00482-2008.

H. Y. Heng and F. Li are with the Department of Electronic and Electrical Engineering, University of Bath, Bath BA2 7AY, U.K. (e-mail: H.Y.Heng@bath.ac.uk; F.Li@bath.ac.uk).

X. Wang is with the Department of Electric Power Engineering, Xi'an Jiaotong University, Shaanxi 710049, China (e-mail: xfwang@mail.xjtu.edu.cn).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TPWRS.2009.2030301

Electricity generation shortages are a potential threat to electricity supplies. Hence, providing adequate generation to meet demand becomes one of the key issues for the market forces in achieving adequate security [1], [2].

The Joint Energy Security of Supply (JESS) group in the U.K., set up in 2001 to examine energy security issues, acknowledges that competitive markets, mostly through price signals, help to provide information for consumers, suppliers, and producers alike to see when supplies are relatively plentiful or tight [3].

The market is designed to encourage electricity prices to rise as the demand for additional capacity increases [2], thus encouraging new and timely generation development.

Adequate generation will require sufficient network to transport energy from points of generation to points of consumption. With ever-rising generation/demand and limited scope in infrastructure development, maintaining network security is more challenging than ever before for network owners/operators [4]. There are two measures that can be taken by network operators to assure availability of network capacity and to ensure the integrity of the network, i.e., withstand credible contingencies to maintain the integrity of the system. One is a technical measure to ensure adequate investment in transmission and distribution infrastructure (building new lines or, when feasible, upgrading existing ones) and efficient operation of the system [1], [5]. The other is a commercial measure to have an efficient network pricing model that reflects the cost imposed on the network from new generation/demand at different locations. The objective is to provide forward-looking economic message to influence the site and size of future generation/demand, and to lead to the least cost to the future network development.

The focus of this paper is on the pricing methodology for the use of system charges. Efficient network charges should closely reflect the extent of use of the system by network users, thus helping to release constraints and congestion in the network, as well as be able to provide efficient economic signals for the network expansion and reinforcement. However, the present pricing methodology adopted by the majority of the distribution networks—the distribution reinforcement model (DRM) in the U.K.—does not provide locational signals as the costs are averaged at each voltage level [6]. The DRM's inability to reflect forward-looking costs and its inconsistency in the treatment between generation and demand increase the difficulty in facilitating the ease of connection of embedded generation.

Forward-looking network prices provide locational signals to network users to act upon. For instance, as network prices for demand increase, distributed generation will be incentivized to connect and demand will be discouraged. This will help in releasing network capacity in more congested areas, and hence in minimizing the future investment cost, which is the main factor in a long-run network pricing methodology. Papers [7] and [8] further illustrate how the network design (planning) process will affect network investment costs. Network investment will increase available or usable capacity, especially from circuits that are operating at or near their maximum capacity and hence increase reliability.

Long-run cost pricing methodologies are recognized as more economically efficient since they reflect the cost to future network reinforcement as a result of nodal demand/generation increment. However, their implementation is often complicated as they involve the allocation of the reinforcement costs among network users [7]–[16]. Up to 2005, investment cost-related pricing (ICRP) is the most advanced long-run pricing model, with pricing based on distance or length of the circuits [17]. One of the recent developments in long-run cost pricing methodology is the long-run incremental cost pricing (LRIC) methodology, developed by the University of Bath in conjunction with Western Power Distribution (WPD) and Ofgem (the regulator of gas and electricity markets in Great Britain) [10]. Its pricing is based on the degree of the circuits' utilization in addition to the circuit distance.

In terms of security, the ICRP charging model used by National Grid of the U.K. does not factor the network security requirement into the charging model; instead, it relies on post-processing through a full-contingency analysis to give an average security factor of 1.86 for all network assets [17]. Reference [10] demonstrated a simplistic approach to network security, which is based on the assumption that reinforcement is needed when a branch reaches its 50% utilization. The importance of network security is also acknowledged in some other works [18]–[20], but none of them translated network security into pricing methodology.

This paper proposes a much enhanced LRIC pricing methodology that adds a number of practical planning considerations in the network pricing. The aim is to significantly improve the applicability of the LRIC pricing in practice. The enhanced LRIC pricing model considers the additional power flow that circuits or transformers have to carry under a full $\mathrm{N}-1$ contingency analysis when pricing the cost of circuits and transformers. This will be contrasted with that from [10] where all assets were assumed to carry an equal amount of additional contingency power flow. The enhanced model also takes into account the effects from differing nodal load growth as seen by planning engineers, instead of a uniform growth rate across the entire network as assumed in [10]. Using the IEEE 14-bus test system and a practical 87-bus distribution network, this paper demonstrates the efficiency of the enhanced LRIC pricing through the comparison in the locational LRIC prices and the resultant revenue recoveries.

In Section II, the basic LRIC pricing methodology is introduced. The principle and the implementation of the enhanced LRIC pricing methodology considering full $\mathrm{N}-1$ contingencies and variable nodal growth rates are presented in Section III. The locational prices and revenue recoveries from the two LRIC pricing methodologies are then illustrated and compared on the IEEE 14-bus test system and a practical distribution network in Sections IV and V, respectively. Finally, Section VI summarizes the contribution of this paper and identifies possible further work.

II. Long-Run Incremental Cost (LRIC) Pricing

Paper [10] proposed the first long-run charging methodology that links the nodal generation/demand increment to changes in circuits and transformers' investment horizon, which is in turn translated into long-run investment cost. The investment horizon is dictated by the present loading level, the load growth rate and circuits' or transformers' spare capacity.

In other words, the LRIC model reflects the asset costs of meeting an increment of generation or demand, which for lines and cables will be a function of distance and also the degree of utilization. For a given load growth rate of a circuit, r_ℓ, the time horizon, n_ℓ, will be the time taken for the load to grow from current loading level of the circuit, D_ℓ, to its full loading level, C_ℓ, as shown in (1). Rearranging (1) gives the equation for time to reinforce (1):

$$C_\ell = D_\ell(1+r_\ell)^{n_\ell} \tag{1}$$

$$n_\ell = \frac{\log C_\ell - \log D_\ell}{\log(1+r_\ell)}. \tag{2}$$

If there is an injection from node N, causing power flow change along a circuit to rise by ΔP_ℓ, then this will advance or delay the future reinforcement, leading to new time horizon-$n_{\ell,new}$ to reinforce. The circuit's long-run incremental cost is the change of its present values PV_ℓ with and without the increment of load, and is then determined using (4):

$$PV_\ell = \frac{Asset_\ell}{(1+d)^{n_\ell}} \tag{3}$$

$$\Delta PV_\ell = Asset_\ell \times \left(\frac{1}{(1+d)^{n_{\ell,new}}} - \frac{1}{(1+d)^{n_\ell}}\right) \tag{4}$$

where d is the discount rate, $Asset_\ell$ is the asset investment cost, and n_ℓ is the time horizon to reinforcement decision. If there is a total of m circuits supporting the power injection from node N, then the long-run incremental cost for node $NLRIC_N$ will be the summation of the changes of present value from all supporting circuits over its nodal injection ΔP_{iN}, as represented by (5):

$$LRIC_N = \frac{\sum \Delta PV}{\Delta P_{iN}}. \tag{5}$$

As mentioned in [14], the LRIC pricing methodology recognizes not only the "distance" power must travel to meet demand but also the degree of circuits' utilization. However, this pricing model does not account for the network security cost required to withstand $\mathrm{N}-1$ contingencies. This would result in less cost-reflective economical signals for future demand and generation siting, which can further jeopardize the efficiency in network investment.

III. LRIC-Security

All networks are designed to be able to withstand credible contingencies, but this comes at a significant cost to network development. For network pricing using LRIC, it is very important to recognize that a significant proportion of the network spare

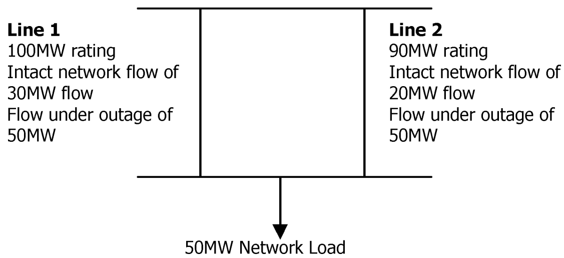

Fig. 1. Two-bus test system.

capacity is reserved for network security. The spare capacity in the LRIC calculation should reflect the maximum allowed loading level for a network asset subject to $\mathrm{N}-1$ contingencies, rather than its rated capacity.

The critical or maximum allowed loading point could either be triggered by a thermal or bus voltage limit or a voltage stability limit (voltage collapse point) [4]. This proposed LRIC pricing places emphasis on assets thermal limits. In the proposed methodology, a security factor for each and every circuit and transformer of the network is obtained by performing an $\mathrm{N}-1$ contingency analysis, where the outage of the most critical circuit is considered.

A. Security Factor With Uniform Load Growth Rate

Fig. 1 shows a busbar system, where Line 1 has a 30-MW flow and Line 2 20 MW flow when there is a 50-MW load connected at busbar 2, assuming no losses. For this simple case, Line 2 outage is the only and the most critical outage for Line 1 and vice versa. We can easily see that when one line is out, the other line will have to carry all the 50-MW power flow to maintain the security of supply. By knowing the power flow at Line 1 during its most critical outage, the security factor (S.F.) of Line 1 can be evaluated using (6):

$$C.F. = \frac{PowerFlow_{Outage}}{PowerFlow_{Original}} = 1.66. \tag{6}$$

Likewise, security factor of Line 2 will be 2.5. Fig. 2 shows the simplified flow chart for security factor calculation.

B. Security Factor With Different Load Growth Rate

Equation (6) assumes uniform load growth rate along each circuit of the network. In reality, different nodes may grow at different rates, leading to potentially very different growth rate for circuits.

If Circuit A is the worst outage for Circuit B, the outage power flow at Circuit B, $S_{B,Out}$, is the sum of the additional contingency flow and the original flow at Circuit B, $S_{B,In}$, where the additional flow at Circuit B is the re-distribution of the original flow of Circuit A when it is out. To account for different load growth rate, a line outage distribution factor (LODF) [21] that defines the size of this re-distribution is introduced into the equation, shown in (7) and (8):

$$S_{B,Out} = LODF \times S_{A,In} + S_{B,In} \tag{7}$$

$$LODF = \frac{S_{B,Out} - S_{B,In}}{S_{A,In}}. \tag{8}$$

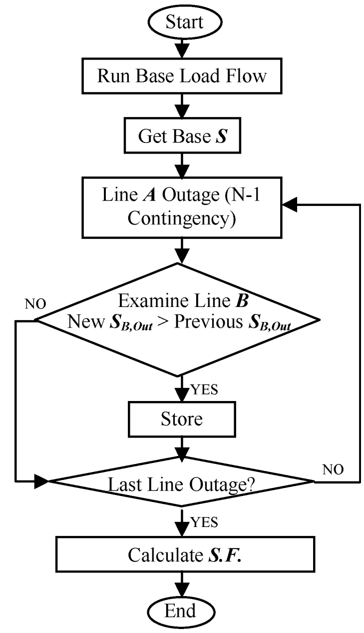

Fig. 2. Simplified flow chart to calculate security factor.

Knowing their respective circuit load growth rate, m, the relationship of the base power flow across the critical line over the base power flow of the examined line can then be found through (9), where r_A and r_B are the load growth rates of Circuit A and Circuit B, respectively. r_A and r_B are computed by examining the power flow change at each circuit as a result of the load increase by a given growth rate:

$$m = \frac{r_A \times S_{A,In}}{r_B \times S_{B,In}} \tag{9}$$

$$S_{B,Out} = (LODF \times m + 1)\, S_{B,In}. \tag{10}$$

Security factor as the ratio of a circuit's worst outage loading level to its original loading level for variable load growth rates can then be redefined in (11). The maximum allowed loading level for Circuit B can then be evaluated by dividing its rated capacity with the S.F.:

$$S.F. = LODF \times m + 1. \tag{11}$$

C. LRIC Considering Network Security

LRIC pricing reflects how a nodal increment might advance or defer the time horizon of future investment. For a given load growth rate, the time horizon of future reinforcement is the time taken for the circuit's loading level rise from the present level to the maximum allowed power flow. To provide efficient long-run signals for future investment and to account for the cost of maintaining the security of supply, it is necessary to find the appropriate requirement of reinforcement for the network circuits. This can be done by adding a security factor in the basic LRIC pricing model.

The rating of the circuit at the design stage is influenced by security factor, which is impacted by the critical outage condition seen by the circuit. With the security factor term, it will make sure that sufficient spare capacity is allocated to ensure network security under the $\mathrm{N}-1$ contingent situation.

TABLE I
CIRCUITS WITH THEIR HIGHEST UTILIZATION HIGHLIGHTED AT THEIR CRITICAL OUTAGE CONDITION

Line [From Bus –> To Bus]	Utilisation (%)																		
	Ori-ginal	Outage L2	Outage L3	Outage L4	Outage L5	Outage L6	Outage L7	Outage L8	Outage L9	Outage L10	Outage L11	Outage L12	Outage L13	Outage L14	Outage L15	Outage L16	Outage L17	Outage T1	Outage T2
1->2	47.63	72.22	45.52	43.23	43.23	49.14	53.68	47.71	47.68	47.83	47.44	47.37	47.62	47.66	47.66	47.63	47.69	47.33	47.50
1->5	38.71	----	49.62	47.10	47.10	36.07	29.70	38.63	38.74	38.83	38.82	39.21	38.80	38.93	38.66	38.71	38.66	39.18	38.89
2->3	37.62	44.61	----	46.30	46.30	50.39	45.62	37.74	37.65	37.77	37.80	37.32	37.57	37.56	37.68	37.62	37.70	37.33	37.49
2->4	41.09	60.97	69.39	----	49.25	32.78	64.94	41.39	41.17	41.46	41.21	40.09	40.95	40.90	41.24	41.09	41.30	40.07	40.65
2->5	30.55	57.05	51.85	49.25	----	24.39	11.40	30.28	30.57	30.56	31.01	31.82	30.80	31.01	30.40	30.55	30.38	31.63	31.00
3->4	17.77	8.87	73.42	6.43	6.43	----	6.47	17.64	17.73	17.62	18.10	18.30	17.82	17.86	17.70	17.76	17.68	18.34	18.00
4->5	34.97	15.78	57.19	55.02	55.02	28.06	----	36.53	35.16	35.96	33.91	28.63	34.14	33.40	35.78	35.01	36.01	28.27	32.25
6->11	29.43	23.77	34.86	33.90	33.90	28.03	62.37	----	31.19	42.67	34.07	60.53	53.71	11.12	14.10	29.89	40.68	55.69	40.19
6->12	29.09	28.37	29.86	29.69	29.69	28.90	33.17	31.61	----	73.73	29.72	33.23	26.98	37.08	30.39	22.64	24.64	31.88	30.43
6->13	50.52	48.37	52.73	52.31	52.31	49.94	62.94	57.85	69.54	----	52.11	62.67	44.47	73.33	54.30	54.71	37.66	59.63	54.66
7->8	15.80	15.77	15.77	15.79	15.79	15.80	15.79	15.79	15.80	15.79	----	15.80	15.80	15.80	15.80	15.80	15.79	15.80	15.79
7->9	25.26	26.82	23.90	24.07	24.07	25.67	17.35	27.92	25.64	27.42	24.12	----	23.52	22.78	26.62	25.33	26.96	15.44	34.27
9->10	23.40	28.81	18.87	20.05	20.05	24.61	25.64	52.60	21.85	11.86	19.02	16.40	----	42.09	38.38	22.97	14.39	30.73	18.12
9->14	35.47	39.21	32.08	32.67	32.67	36.42	19.90	23.68	39.61	62.14	33.28	17.12	45.51	----	29.33	36.33	57.08	26.85	29.21
10->11	15.13	9.55	20.46	19.60	19.60	13.75	48.40	14.10	16.87	28.07	19.89	45.63	38.60	5.84	----	15.58	26.22	43.28	26.18
12->13	6.43	5.72	7.12	6.96	6.96	6.27	10.39	8.84	22.71	48.85	7.15	10.39	4.40	14.16	7.66	----	2.46	9.24	7.66
13->14	21.19	17.55	24.69	24.13	24.13	20.23	42.36	33.13	17.09	7.45	23.81	41.03	11.32	57.50	27.37	20.34	----	38.26	28.26
4->7	32.98	34.34	31.30	31.40	31.40	33.52	22.24	35.06	33.25	34.39	30.72	19.44	32.07	30.99	34.04	33.02	34.39	----	43.78
4->9	26.80	28.31	25.26	25.39	25.39	27.28	17.14	29.28	27.14	28.69	26.96	51.17	25.37	24.45	28.06	26.85	28.42	52.14	----
5->6	45.34	42.73	48.22	47.73	47.73	44.56	61.71	40.78	44.98	42.81	46.90	60.88	48.96	50.87	42.91	45.23	42.41	58.09	50.91

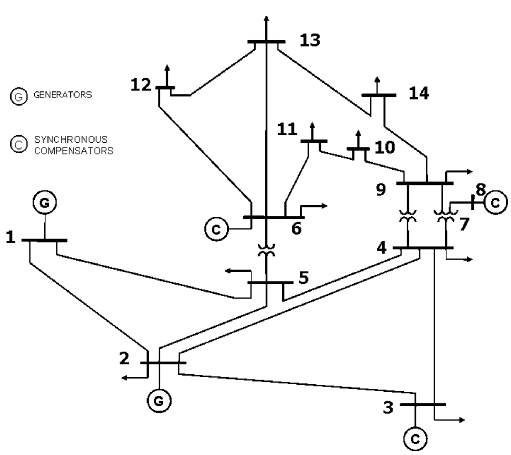

Fig. 3. IEEE 14-bus test system.

For a given load growth rate r, the time horizon of future investment will be the time taken for the load to grow from current loading level D to the maximum or requirement of reinforcement loading margin (under $\mathrm{N}-1$ contingency), $C/S.F.$, instead of C, the full loading level (rated capacity). The time horizon, present value of the assets, and finally the new LRIC cost are then obtained, with the $S.F.$ term:

$$\frac{C_\ell}{S.F.} = D_\ell(1+r_\ell)^{n_\ell}. \tag{12}$$

IV. CASE STUDY 1

This section compares the proposed approach with the basic LRIC pricing on the IEEE 14-bus test system shown in Fig. 3. The system consists of 14 buses, 17 lines, three transformers, two generators, and three synchronous condensers. Buses 1, 2, 3, 4, and 5 are at 132-kV voltage level and the other buses are at 33-kV voltage level. The peak demand of the system is 260 MW [22].

By running an $\mathrm{N}-1$ security assessment, the security factor of each lines and transformers are obtained. LRIC charges with and without any security consideration are then compared.

A. Security Factor and Maximum Allowed Loading Level

Table I shows 18 valid outage conditions and their respective impacts to the degree of assets' utilization. For example, line connecting Bus 1 to Bus 2 has its utilization raised from 47.63% to 72.22% (the most critical) as a result of Outage L2 (outage of the line connecting Bus 1 to Bus 5).

Tables II and III show the results of the maximum allowed loading level (MALL) of the lines and transformers and their respective security factor for each asset. For a uniform growth rate, the security factor generated from the maximum allowed power flow and the base flow varies widely from 1.00 to 7.54. The will significantly impact on the time horizon of future reinforcement, which will in turn impact on the long-run locational prices. This also implies that long-run cost evaluation without security consideration (i.e., considering S.F. equals to 1) is considerably under-evaluating the cost to the network from a nodal increment.

Fig. 4 depicts the maximum allowed loading level for each line, from the $\mathrm{N}-1$ contingency analysis, and its rated capacity. Fig. 4 suggests that this maximum allowed loading level, under $\mathrm{N}-1$ contingency, could be hugely different compared to the rated capacity. For instance, Line 6, i.e., the line connecting Bus 3 to Bus 4, has a MALL value of 32.83 MVA which is just a quarter of its rated capacity.

According to Table I, the worse outage that caused a large contingency flow (75.1 MVA) on Line 6 is Outage L3 (the line connecting Bus 2 to Bus 3). Line 3 has an original flow of 72.3 MVA, and the highest power flow in the network. When Line 3 is out, Line 6 has to carry all the power flow to supply the load at Bus 3 (Fig. 5). This means that about 75% of Line 6's capacity

TABLE II
MAXIMUM ALLOWED LOADING LEVELS AND SECURITY FACTOR FOR LINES

Line	From	To	Base Loading Level (MVA)	Maximum Allowed Loading Level (MVA)	S.F.
1	BUS001	BUS002	329.84	218.44	1.51
2	BUS001	BUS005	192.20	151.34	1.27
3	BUS002	BUS003	192.29	143.50	1.34
4	BUS002	BUS004	135.26	80.51	1.68
5	BUS002	BUS005	135.22	72.31	1.87
6	BUS003	BUS004	134.93	32.83	4.11
7	BUS004	BUS005	179.63	110.88	1.62
8	BUS006	BUS011	28.05	13.43	2.09
9	BUS006	BUS012	27.98	11.06	2.53
10	BUS006	BUS013	37.66	26.15	1.44
11	BUS007	BUS008	114.26	114.26	1.00
12	BUS007	BUS009	114.47	84.17	1.36
13	BUS009	BUS010	27.95	12.10	2.31
14	BUS009	BUS014	28.05	15.94	1.76
15	BUS010	BUS011	27.96	9.05	3.09
16	BUS012	BUS013	28.05	3.72	7.54
17	BUS013	BUS014	28.05	10.50	2.67

TABLE III
MAXIMUM ALLOWED LOADING LEVELS AND SECURITY FACTOR FOR TRANSFORMERS

Trans-former	From	To	Base Loading Level (MVA)	Maximm Allowed Loading Level (MVA)	S.F.
1	BUS004	BUS007	89.67	67.93	1.32
2	BUS004	BUS009	60.06	30.80	1.95
3	BUS005	BUS006	100.20	73.68	1.36

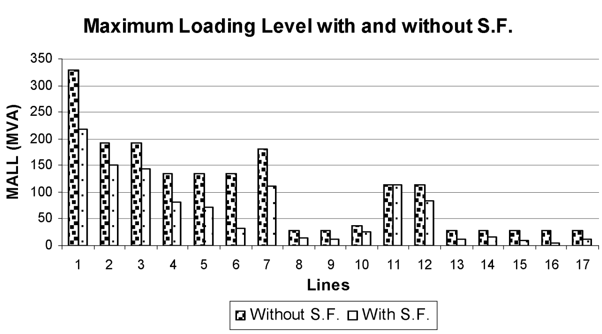

Fig. 4. Maximum allowed loading level with and without security consideration.

needs to be reserved to accommodate power flow at L3 should this line be out.

The lesser the MALL, the smaller will be the spare capacity, the future reinforcement will be closer, and this will give rise to the reinforcement cost of the asset.

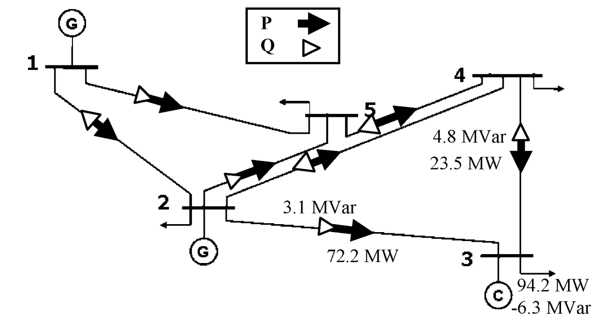

Fig. 5. Directions of the power flow for the 132-kV part of the system.

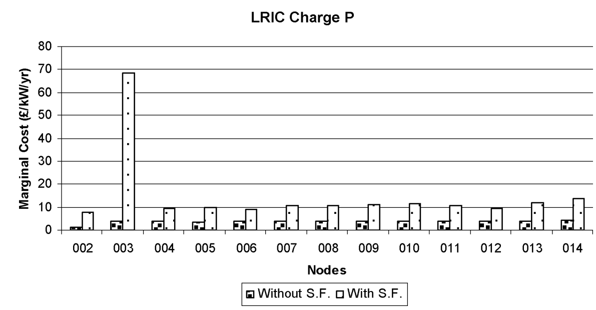

Fig. 6. LRIC charges (for real power, P) comparison with and without security factor (using LRIC).

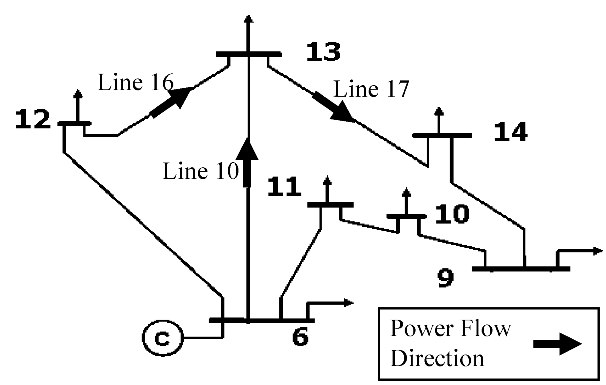

Fig. 7. Directions of the power flow for the 33-kV part of the system.

B. Long-Run Incremental Cost Pricing

The significant difference of the MALL and the rated capacity of Line 6 are immediately reflected in the LRIC price at Bus 3 (Fig. 6), which is supported by Lines 3 and 6.

This is followed by the prices at Buses 13 and 14, which are supported by the line with the highest security factor (Line 16). The LRIC price at Bus 14 is greater than that of Bus 13 due to the way that power distributed at the distribution level. As shown by Fig. 7, power flows into Bus 13 through Line 10 and 16 and flows out to Bus 14 through line 17. Therefore, a load withdrawal at Bus 14 causes a power flow increase on all three supporting lines. As for Bus 13, a load withdrawal at the point has increased power flow for line 10 and 16 but decreased power flow for line 17, and hence reduces prices. This further reinforces the finding in [23].

Fig. 8 shows reactive power prices against each node in the network. LRIC prices for reactive power is based on the MW+MVAr-Mile method presented in [24]. The figure shows

TABLE IV
REVENUE RECOVERY TABLE WITHOUT SECURITY CONSIDERATION

Node	Generation P (MW)	Generation Q (MVAr)	Load P (MW)	Load Q (MVAr)	LRIC Charge P (£/KW/Yr)	LRIC Charge Q (£/KVAr/Yr)	Revenue Recovered P (£/Yr)	Revenue Recovered Q (£/Yr)	Revenue Recovered Total (£/Yr)
002	-40.0	-44.1	21.7	12.7	1.36	-0.21	-24943	6509	-18434
003	0.0	-25.3	94.2	19.0	4.02	-0.29	378213	-1857	376356
004	0.0	0.0	47.8	-3.9	3.90	-0.26	186229	-1002	185227
005	0.0	0.0	7.6	1.6	3.35	-0.16	25422	-256	25166
006	0.0	-13.8	11.2	7.5	3.65	-0.21	40914	-1304	39610
007	0.0	0.0	0.0	0.0	3.90	-0.27	0	0	0
008	0.0	-18.3	0.0	0.0	3.90	-0.26	0	-4711	-4711
009	0.0	0.0	29.5	-2.4	3.87	-0.27	114106	-636	113470
010	0.0	0.0	9.0	5.8	3.88	-0.25	34929	-1444	33485
011	0.0	0.0	3.5	1.8	3.81	-0.22	13342	-391	12951
012	0.0	0.0	6.1	1.6	3.88	-0.17	23674	-277	23397
013	0.0	0.0	13.5	5.8	3.95	-0.16	53298	-911	52387
014	0.0	0.0	14.9	5.0	4.11	-0.19	61284	-970	60314
							Total		899218

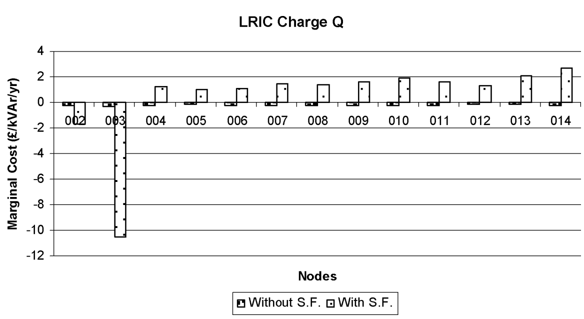

Fig. 8. LRIC charges (for reactive power, Q) comparison with and without security factor (using LRIC).

the impact to the long-run network reinforcement cost from a unit MVAr injection at each study node.

Without security factor, all the prices for the reactive power (Fig. 8) are small negative values. This suggests that there is excessive reactive power in the system, which is not the case when the network is required to withstand all $N-1$ contingencies.

With security factor, Bus 2 has a large negative price. This is due to the counter flow created in line 1 as the result of a reactive power injection at Bus 2. This effect is shown in Fig. 5.

The LRIC charge at Bus 3 has the largest negative value as a reactive power injection at Bus 3 has a large impact to the network, causing counter flows on Lines 1, 4, 6, and 7.

The prices shown in Figs. 6 and 8 depict the price for load. As for generation, the prices are obtained by applying an increment of generation at each node. Hence, the generation prices are the negative of the load prices that reflect the opposite effects in reinforcement horizon as a result of nodal generation increment.

Generally, the results suggest that the prices for LRIC without security factor are significantly smaller but less cost-reflective compared to the prices with security factor. When the network security is not being taken into account in the cost evaluation by the original LRIC pricing model, the circuit loading level is allowed to reach to its rated capacity. As for the new LRIC methodology, the pricing is able to separate the spare capacity for network security from the effective spare capacity, providing more cost-reflective long-run pricing in network charges.

C. Revenue Recovery

Table V summarizes nodal generation/demand, nodal real and reactive power prices, and the revenue recovery without considering security, while Table V gives the results considering security. With significantly higher prices, the LRIC methodology with security factor can recover considerably more revenue, rising from 10.4% to 91.4%. This would leave less room for revenue reconciliation, and hence, less distortion to the pure economic message.

For the basic LRIC methodology, generation (at Bus 2) collects $-£18\,434$ per year while load across the network pays £917 652 per year after revenue recovery. As for LRIC with security consideration, generation earnings increase by around fivefold to $-£90\,238$ per year and load payments increase to £8 003 684 per year.

V. CASE STUDY 2

To demonstrate its practicality, the proposed approach is applied on an 87-bus practical distribution network shown in Fig. 9. This network consists of 56 lines, 54 transformers, and three generators. The lines consist of both overhead lines and underground cables. The underground cables have much higher cost per km compared to the overhead lines. The P and Q LRIC charges with and without security factor are shown in Figs. 10 and 11.

As shown in Fig. 10, the highest price for real power withdrawal (for LRIC-security) is at Bus 3009 where the main supporting line, line connecting Buses 2015 and 3012, is the longest line in the network, 20.9 km. Nevertheless, the length of the line is not the only factor affecting the price. For instance, load at Bus 3015 supported by another long line (20.1 km) is charged much less. This is because the main supporting branches of Bus 3015 have to support relatively a small proportion of contingency flow, which consequently results in large spare capacity

TABLE V
REVENUE RECOVERY TABLE WITH SECURITY CONSIDERATION

Node	Generation		Load		LRIC Charge		Revenue Recovered		
	P (MW)	Q (MVAr)	P (MW)	Q (MVAr)	P (£/KW/Yr)	Q (£/KVAr/Yr)	P (£/Yr)	Q (£/Yr)	Total (£/Yr)
002	-40.0	-44.1	21.7	12.7	7.90	-1.73	-144479	54241	-90238
003	0.0	-25.3	94.2	19.0	68.62	-10.57	6464381	-67022	6397359
004	0.0	0.0	47.8	-3.9	9.53	1.22	455438	4762	460200
005	0.0	0.0	7.6	1.6	9.92	0.99	75362	1587	76949
006	0.0	-13.8	11.2	7.5	9.03	1.09	101114	6868	107982
007	0.0	0.0	0.0	0.0	10.62	1.44	0	0	0
008	0.0	-18.3	0.0	0.0	10.64	1.36	0	24909	24909
009	0.0	0.0	29.5	-2.4	11.04	1.65	325592	3962	329554
010	0.0	0.0	9.0	5.8	11.34	1.92	102051	11148	113199
011	0.0	0.0	3.5	1.8	10.49	1.64	36719	2959	39678
012	0.0	0.0	6.1	1.6	9.39	1.32	57303	2104	59407
013	0.0	0.0	13.5	5.8	12.03	2.06	162432	11954	174386
014	0.0	0.0	14.9	5.0	13.88	2.67	206738	13325	220063
							Total		7913447

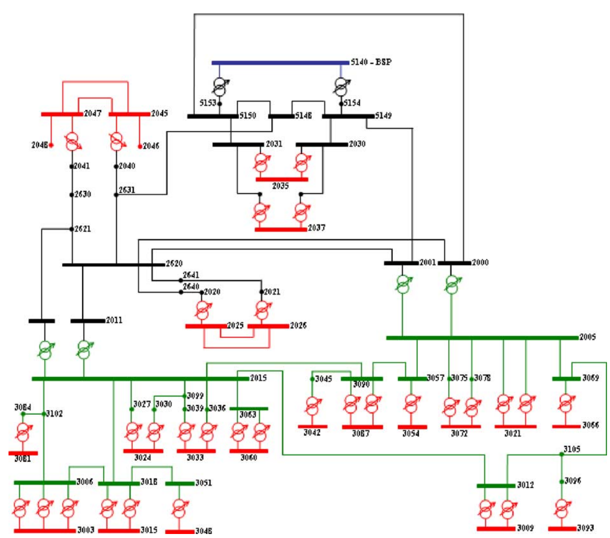

Fig. 9. The 87-bus practical distribution network.

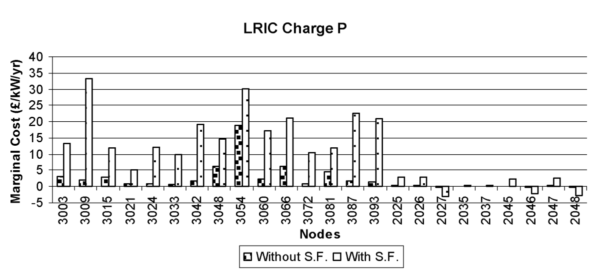

Fig. 10. LRIC charge (for real power, P) comparison with and without security factor.

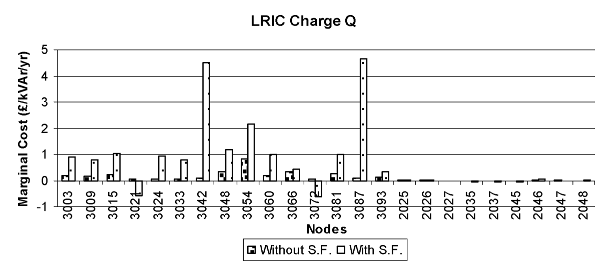

Fig. 11. LRIC charge (for reactive power, Q) comparison with and without security factor.

TABLE VI
DATA OF THE MAIN SUPPORTING BRANCHES OF BUS 3009

From Bus	To Bus	S.F.	MALL (MVA)	Current Loading Level (MVA)
Transformers:				
3012	3009	2.00	5.70	5.29
3012	3009	2.02	5.65	5.24
Line:				
2015	3012	2.63	8.25	7.56

TABLE VII
DATA OF THE MAIN SUPPORTING BRANCHES OF BUS 3015

From Bus	To Bus	S.F.	MALL (MVA)	Current Loading Level (MVA)
Transformers:				
3018	3015	2.00	8.97	4.03
3018	3015	2.02	8.88	3.99
Line:				
2015	3018	1.23	13.97	9.43

and small effective circuit utilizations (Table VII), compared to those of Bus 3009 (Table VI).

The next highest price is at Bus 3054, which is mainly due to the highly utilized (96%) single transformer that is supporting the load. In addition, the main supporting line connecting Buses 2005 and 3057 consist of a 4.7-km underground cable. This cable is the longest amongst all the 33-kV underground cables and has a significant contribution to the line's high asset cost.

The revenue recovered from using the LRIC prices without security consideration is 7.6%, while LRIC-security recovers 45.8%, which again leaves less room for revenue reconciliation.

LRIC-security not only takes into account the length and effective utilization of the supporting branches but also leads to a better revenue recovery that is closer to the target compared to the basic LRIC.

VI. Conclusion

This paper presented a new approach to account for the cost of security in a long-run network pricing model. The proposed approach relates the nodal increment of generation/demand to the long-run incremental cost to a network, where the incremental cost reflects the network security in addition to distance travelled and the degree of circuits' utilization. For the first time, network security can be reflected in a pricing model by adding a security term into the methodology, which is obtained by running a full $\mathrm{N}-1$ contingency analysis. This security factor term reflects the additional power flow a branch has to carry when its most critical contingency takes place.

The security factor would reduce the unused capacity of a branch and thus brought forward the time horizon of the future reinforcement, and hence increases the incremental cost. Further, it has significantly increased the revenue recovery, leaving less room for distorting the pure economic message. In this case, the new methodology recovers 91.4% of the revenue, which is 81% more than the LRIC methodology without security consideration for the IEEE 14-bus test system and recovers 38.2% more revenue for the practical 87-busbar system.

In conclusion, the new pricing methodology is simple, more cost-reflective, transparent, and able to provide more efficient locational signals for potential generation and demand customers. This will in turn incentivize a more efficient network to evolve in the future.

References

[1] C. Ray, Power System Planning: System Development—Maintaining Security, U.K. [Online]. Available: http://www.iea.org/Textbase/work/2004/transmission/ray2.pdf.

[2] Security of Electricity Supplies, Parliamentary Office of Science and Technology, 2003, POSTnote 203.

[3] The Joint Energy Security of Supply Group Report, Department of Trade and Industry, 2006.

[4] F. Milano, C. A. Canizares, and M. Invernizzi, "Multiobjective optimization for pricing system security in electricity markets," *IEEE Trans. Power Syst.*, vol. 18, no. 2, pp. 596–604, May 2003.

[5] Security of Supply in Electrcity Markets- Evidence and Policy Issues, International Energy Agency, Paris, France, 2002. [Online]. Available: http://www.iea.org/dbtw-wpd/textbase/nppdf/free/2000/security2002.pdf.

[6] F. Li, N. P. Padhy, J. Wang, and B. Kuri, "Cost-benefit reflective distribution charging methodology," *IEEE Trans. Power Syst.*, vol. 23, no. 1, pp. 58–64, Feb. 2008.

[7] D. Shirmohammadi *et al.*, "Some fundamental, technical concepts about cost based transmission pricing," *IEEE Trans. Power Syst.*, vol. 11, no. 2, pp. 1002–1008, May 1996.

[8] P. Williams and S. Andrews, *Distribution Network Connection: Charging Principles and Options*. London, U.K.: DTI, 2002.

[9] F. Li *et al.*, Network Benefits From Introducing an Economic Methodology for Distribution Charging, 2006. [Online]. Available: http://www.ofgem.gov.uk/ofgem/work/ index.jsp?section=/areasofwork/distributioncharges.

[10] F. Li and D. L. Tolley, "Long-run incremental cost pricing based on unused capacity," *IEEE Trans. Power Syst.*, vol. 22, no. 4, pp. 1683–1689, Nov. 2007.

[11] D. Shirmohammadi, C. Rajgopalan, E. R. Alward, and C. L. Thomas, "Cost of transmission transactions: An introduction," *IEEE Trans. Power Syst.*, vol. 6, no. 3, pp. 1006–1016, Aug. 1991.

[12] H. H. Happ, "Cost of wheeling methodologies," *IEEE Trans. Power Syst.*, vol. 9, no. 1, pp. 147–156, Feb. 1994.

[13] R. R. Kovacs and A. L. Leverett, "A load flow based method for calculating embedded, incremental and marginal cost of transmission capacity," *IEEE Trans. Power Syst.*, vol. 9, no. 1, pp. 272–278, Feb. 1994.

[14] J. M. Lima and E. Oliveira, "The long term impact of transmission pricing," *IEEE Trans. Power Syst.*, vol. 13, no. 4, pp. 1514–1520, Nov. 1998.

[15] M. T. Ponce de Leao and J. T. Saraiva, "Solving the revenue reconciliation problem of distribution network providers using long-term marginal prices," *IEEE Trans. Power Syst.*, vol. 13, no. 1, pp. 448–454, Feb. 2000.

[16] A. Bakirtzis *et al.*, "Comparison of two methods for long-run marginal cost based transmission use of system pricing," *Proc. Inst. Elect. Eng., Gen., Transm., Distrib.*, vol. 148, no. 4, pp. 477–481, Jul. 2001.

[17] The Statement of the Use of System Charging Methodology, The Charging Team. National Grid, U.K. [Online]. Available: http//www.nationalgrid.com/uk/indifo/charging/pdfs.UoSC_Apr_03_(I3R0).pdf.

[18] G. Strbac and N. Jenkins, Network Security of the Future UK Electricity System, PIU, U.K., 2001. [Online]. Available: http://www.tyndall.uea.ac.uk /research/theme2/Network_Security_UMIST.pdf.

[19] J. Mutale, G. Strbac, and D. Pudjianto, "Methodology for cost reflective pricing of distribution networks with distributed generation," in *Proc. IEEE Power Eng. Soc. General Meeting*, 2007.

[20] D. Pudjianto, G. Strbac, and J. Mutale, "Access and pricing of distribution network with distributed generation," in *Proc. IEEE Power Eng. Soc. General Meeting*, 2007.

[21] R. D. Christie, B. F. Wollenberg, and I. Wangensteen, "Transmission management in the deregulated environment," *Proc. IEEE*, vol. 88, pp. 170–195, 2000.

[22] Power Systems Test Case Archive, College of Engineering, University of Washington. [Online]. Available: http://www.ee.washington.edu /research/pstca/.

[23] H. Y. Heng, J. Wang, and F. Li, "Comparison between long-run incremental cost pricing and investment cost-related pricing for electricity distribution network," in *Proc. CIRED*, Vienna, Austria, 2007.

[24] F. Li *et al.*, "Development of a novel MW+MVAr-Miles charging methodology," in *Proc. IEEE/PES Transmission and Distribution Conf. Exhib.: Asia and Pacific*, 2005.

Hui Yi Heng (S'07) was born in Miri, Malaysia. She received the B.Eng. degree in electrical and electronics engineering from the University of Bath, Bath, U.K., in 2005. She is currently pursuing the Ph.D. degree in the Power and Energy System Group at the University of Bath, in the field of power system economics, pricing, and planning.

Her major research interest is in the area of power system planning, analysis, and power system economics.

Furong Li (M'00–SM'09) was born in Shanxi, China. She received the B.Eng. degree in electrical engineering from Hohai University, Nanjing, China, in 1990 and the Ph.D. degree in 1997 with a dissertation on "Applications of genetic algorithms in optimal operation of electrical power systems."

She is a Senior Lecturer in the Power and Energy System Group at the University of Bath, Bath, U.K. Her major research interest is in the area of power system planning, analysis, and power system economics.

Xifan Wang (SM'96–F'09) graduated from Xi'an Jiaotong University, Xi'an, China, in 1957. He has since been with the School of Electrical Engineering of Xi'an Jiaotong University, where he now holds the rank of Professor. His research fields include power system analysis, generation planning and transmission system planning, reliability evaluation, and power market. He has authored and coauthored ten books and more than 200 journal and conference papers on the above subjects.